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Baryogenesis from the Kobayashi-Maskawa Phase

Micha Berkooz,[1,*] Yosef Nir,[1,†] and Tomer Volansky[1,‡]

[1]Department of Particle Physics, Weizmann Institute of Science, Rehovot 76100, Israel

The Standard Model fulfills the three Sakharov conditions for baryogenesis. The smallness of quark masses suppresses, however, the CP violation from the Kobayashi-Maskawa phase to a level that is many orders of magnitude below what is required to explain the observed baryon asymmetry. We point out that if, as a result of time variation in the Yukawa couplings, quark masses were large at the time of the electroweak phase transition, then the Kobayashi-Maskawa mechanism could be the source of the asymmetry. The Froggatt-Nielsen mechanism provides a plausible framework where the Yukawa couplings could all be of order one at that time, and settle to their present values before nucleosynthesis. The problems related to a strong first order electroweak phase transition may also be alleviated in this framework. Our scenario reveals a loophole in the commonly held view that the Kobayashi-Maskawa mechanism cannot be the dominant source of CP violation to play a role in baryogenesis.

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Introduction. The Standard Model (SM) fulfills all three of Sakharov conditions [1] for generating a baryon asymmetry in the Universe. The model fails, however, to explain the observed value of the asymmetry, $n_B/s \sim 10^{-10}$, for two reasons:

1. CP violation from the Kobayashi-Maskawa (KM) mechanism [2] is highly suppressed. Explicitly, the relevant suppression factor [3] is given by

$$\epsilon_{\rm CP} = \frac{1}{T_c^{12}} \prod_{\substack{i>j \\ u,c,t}} (m_i^2 - m_j^2) \prod_{\substack{i>j \\ d,s,b}} (m_i^2 - m_j^2) J_{\rm CP} \sim 10^{-19}, \tag{1}$$

   where $T_c \simeq 100$ GeV is the critical temperature at which the electroweak phase transition (EWPT) takes place, and $J_{\rm CP}$ is a combination of CKM parameters, $J_{\rm CP} \sim s_{12}s_{23}s_{13}\sin\delta_{\rm KM}$.

2. The EWPT is not strongly first order. The experimental lower bound on the Higgs mass, $m_H > 114$ GeV, implies that the EWPT is second order. Consequently, sphaleron-induced $(B+L)$-violating interactions are not sufficiently suppressed in the broken phase and wash out the baryon asymmetry.

Both failures are related to the numerical values of the Standard Model parameters. Had quark masses been heavier, the suppression factor of eq. (1) would be milder. Had the Higgs mass been lighter, the EWPT could be first order. Therefore, if quark and Higgs masses have been subject to time variations, it is possible that the Standard Model baryogenesis is the only source of the observed baryon asymmetry. In this paper, we explore this idea, with focus on four main issues:

1. We are assuming that the Yukawa couplings have been time-varying. Is it plausible that the variation was such that they all had been of order one in early times?

2. Cosmology implies that the Yukawa couplings had values close to their present ones at the time of nucleosynthesis (NS). Is it plausible that the required time variation took place between EWPT and NS?

3. Can we estimate the baryon asymmetry that is produced at the EWPT by the KM mechanism with all quark masses of $\mathcal{O}(m_W)$?

4. What are the implications of time varying couplings on the strength of the EWPT?

The Froggatt-Nielsen Mechanism. The smallness and the hierarchy in the Yukawa couplings are unexplained within the SM. One of the more attractive frameworks where these features find a natural explanation is the Froggatt-Nielsen (FN) mechanism [4]. In this framework, one invokes a horizontal Abelian symmetry. Fields of different generations carry different charges under the symmetry. The symmetry is spontaneously broken by a VEV of a SM-singlet scalar field S. The breaking is communicated to the SM fields through intermediate quarks and leptons in vector-representations of the SM gauge group, which have large masses at a scale M. The ratio $\lambda \equiv \langle S\rangle/M$ is assumed to be small, $\lambda \ll 1$. Normalizing the horizontal charges by defining the charge of S to be -1, effective Yukawa couplings suppressed by $\lambda^{|n|}$ are induced for terms that carry charge n under the FN symmetry.

In the simplest FN models, the horizontal group is Z_N or $U(1)$, and it is broken by a single scalar field. The value of λ is often taken to be of order 0.2 (the value of the Cabibbo angle). A typical set of FN charges for the quark doublet (Q_i) and antiquark singlet ($\bar U_i$ and $\bar D_i$) fields is the following:

$$\begin{array}{ccc} Q_3(0), & Q_2(+2), & Q_1(+3), \\ \bar U_3(0), & \bar U_2(+1), & \bar U_1(+4), \\ \bar D_3(+2), & \bar D_2(+2), & \bar D_1(+3), \end{array} \tag{2}$$

leading to the following parametric suppression of the flavor parameters (with the FN charge of the Higgs field set to zero):

$$\begin{aligned} &Y_t \sim 1, \quad Y_c \sim \lambda^3, \quad Y_u \sim \lambda^7, \\ &Y_b \sim \lambda^2, \quad Y_s \sim \lambda^4, \quad Y_d \sim \lambda^6, \\ &s_{12} \sim \lambda, \quad s_{23} \sim \lambda^2, \quad s_{13} \sim \lambda^3. \end{aligned} \tag{3}$$

With the KM phase being of order one, the suppression factor of eq. (1) is $\epsilon_{\rm CP} \sim \lambda^{28}$.

It is not unlikely that the VEVs of scalar fields have been time varying. Such a variation could happen for various reasons. One possibility is that at high enough temperatures, $H \sim T^2/m_{\rm Pl} \gg m$, where m is the mass of the scalar, the scalar may be frozen away from the minimum. Another possibility is that the minimum of the scalar potential has shifted as a result of finite temperature effects. Let us consider the case where, for one reason or another, the value of $\langle S\rangle$ has been time varying, with $\langle S\rangle \sim M$ prior to the EWPT, compared to its present value of order $0.2M$. Note that we are considering a rather mild shift, by a factor of order five. Such a modest variation would, however, change the Yukawa couplings in a drastic way. There will be no small parameter to suppress them, and they are all of order one. In particular, at the EWPT

$$\epsilon_{\rm CP}(T \sim T_c) = \mathcal{O}(1). \tag{4}$$

We learn that in the FN framework, a time variation such that at early times there is neither smallness nor strong hierarchy in the Yukawa couplings is not a contrived scenario. Since the smallness of $\epsilon_{\rm CP}$ is a result of its dependence on a very high power of a mildly small parameter, once that single parameter is order one, there is no suppression of $\epsilon_{\rm CP}$.

Shifting $\langle S\rangle$ between EWPT and NS. Our scenario requires that the scalar field S is frozen away from its present minimum until the EWPT, but to assume its present value before nucleosynthesis. The simplest mechanism that ensures that the scalar is frozen until the EWPT but starts to oscillate and redshift shortly afterwards is by giving it a mass that is close to the Hubble constant at the time of the EWPT, $H_{\rm EWPT} = \mathcal{O}(10^{-15}$ GeV). Such a light scalar poses, however, problems to cosmology which are known as 'the moduli problem':

- Light stable scalars should have masses lighter than the Hubble constant at the time of matter-radiation equality, $H_{\rm eq} = \mathcal{O}(10^{-37}$ GeV), in order not to dominate the energy density of the Universe from rather early times.

- Light unstable scalars should have decay rates faster than Hubble constant at the time of nucleosynthesis, $H_{\rm ns} = \mathcal{O}(10^{-25}$ GeV).

Since $m_S \sim 10^{-15}$ GeV, it is too heavy to fulfill the first condition. Moreover, to avoid being too long lived to fulfill the second condition, S must decay to final photons or neutrinos with an effective coupling larger than $\mathcal{O}(10^{-5})$. An explicit calculation, assuming that nonrenormalizable couplings are suppressed by powers of $m_{\rm Pl}$, shows that the actual couplings are much smaller than that.

Various ways to solve the moduli problem have been suggested in the literature (see *e.g.* [5]). Here, we present a model where the problem is circumvented. Other possible solutions will be explored in [6].

The usual scenarios assume that the scalar potential does not change during the cosmological evolution. We present here a simple model where the potential does change at the EWPT. Thus, it is not the fast expansion which freezes S but rather the potential itself. This situation allows for a larger m_S which, in turn, gives a fast enough decay rate.

Consider the following potential for the scalar S and the SM Higgs field ϕ:

$$\begin{aligned} V(S,\phi) \;&=\; m_W^4 f\left(\frac{S^\dagger S}{M^2}\right) - \mu_\phi^2 \phi^\dagger\phi\left[1+g\left(\frac{S^\dagger S}{M^2}\right)\right] \\ &+\; \lambda_\phi(\phi^\dagger\phi)^2\left[1+h\left(\frac{S^\dagger S}{M^2}\right)\right]. \end{aligned} \tag{5}$$

Before EWPT, we have $V(S) = m_W^4 f$. After EWPT, we have $V(S) = m_W^4 f - \mu_\phi^2\langle\phi\rangle^2(1+g) + \lambda_\phi\langle\phi\rangle^4(1+h)$. We learn that the required shift of $\langle S\rangle$ from M to λM can occur naturally during the EWPT.

For $M \approx m_{\rm Pl}$, we still run into the cosmological moduli problem. Assuming that the nonrenormalizable S couplings to SM fields are suppressed by powers of M and that its mass is of order m_W^2/M (as is the case for the potential (5)), we find that the leading decay mode is $S \to \gamma\gamma$ giving $\Gamma \sim m_S^3/M^2$. Requiring that S decays before nucleosynthesis, we obtain $M \lesssim 10^7$ GeV. This upper bound on M implies that $m_S \gtrsim$ MeV.

The mass $m_S \gtrsim$ MeV and the decay width $\Gamma_S \gtrsim 10^{-25}$ GeV lie outside of the regions excluded by various astrophysical and cosmological considerations and by direct laboratory searches [7]. A lower bound on M arises from the contribution of S-mediated tree diagrams to flavor changing neutral current processes. Estimating $\Delta m_K/m_K \sim [(m_d m_s)/(\lambda^2 M^2)](f_K^2/m_K^2)$ (and analogous relations for D- and B-mixing), we obtain $M \gtrsim 5\times 10^5$ GeV, consistent with the nucleosynthesis constraint.

In spite of the fact that $M \ll m_{\rm Pl}$, S would start rolling only at the EWPT because earlier it is stabilized by the potential rather than by the expansion.

One may ask whether it is possible to have a full high energy theory that induces (5) in a natural way. We have been able to construct a supersymmetric model with a horizontal Z_N symmetry (in the spirit of models for the scalar potential in ref. [8]) where this is the case. A very

large N is, however, required in order to make the model consistent with all our requirements. We are presently exploring other models [6].

Suppression from CP Violation. The possibility that the Standard Model accounts for baryogenesis is intriguing [9], but in the end the suppression from the Kobayashi-Maskawa CP violation [$\epsilon_{\rm CP}$ of eq. (1)] is too strong for it to make a significant contribution [10, 11]. (For SM values of the flavor parameters, this statement holds model independently and, in particular, independent of the dynamics of the phase transition [10].) The situation is of course different in our scenario, where $\epsilon_{\rm CP} = \mathcal{O}(1)$. We now explain which of the usual suppression factors related to CP violation are lifted in our scenario and which are not. We also explain why the analysis of the SM baryogenesis [10] cannot be simply applied to our case. (An analysis of SM baryogenesis with quark masses of $\mathcal{O}(T_c)$ is beyond the scope of this paper [6].)

During the EWPT, a bubble of the true vacuum ($\langle\phi\rangle = v \neq 0$) expands, sweeping out space until it becomes our observed universe. While the bubble expands, equal number of quarks and antiquarks hit the bubble wall, some reflected and some transmitted through the wall. CP violating interactions induce an asymmetric distribution of quarks and antiquarks. In a simplified picture where baryon-number violating interactions are infinitely fast in the unbroken phase, but do not exist in the broken phase, an excess of baryon number outside the bubble is immediately washed out while an opposite amount of baryon number is preserved inside. One can then calculate n_B/s. Taking the thin wall approximation, ref. [10] obtains (to leading order in the wall velocity v_W)

$$\frac{n_B}{s} \simeq \frac{10^{-3}}{T^2}\int \frac{d\omega}{2\pi} n_0(\omega)(1-n_0(\omega))\Delta(\omega)(\vec{p}_L - \vec{p}_R)\cdot\hat{v}_W. \tag{6}$$

Here $n_0(\omega) = 1/(e^{\omega/T}+1)$ is the Fermi-Dirac distribution, and $\vec{p}_{L,R}$ are the left-handed/right-handed quark momenta. The reflection asymmetry $\Delta(\omega)$ is given by ${\rm Tr}(\bar{R}^\dagger_{LR}\bar{R}_{LR} - R^\dagger_{LR}R_{LR})$ where $R_{LR}(\bar{R}_{LR})$ is the reflection coefficient for $q_L \to q_R$ ($\bar{q}_R \to \bar{q}_L$).

In the standard scenario, the main suppression factor of n_B/s comes from $\Delta(\omega) \sim \epsilon_{\rm CP}$. This is expected on general grounds, since the KM mechanism of CP violation is operative if and only if $\epsilon_{\rm CP} \neq 0$. For Yukawa couplings of order one, however, this suppression factor is entirely lifted. Another, milder suppression comes from $(\vec{p}_L - \vec{p}_R)\cdot\hat{v}_W/T \sim \alpha_W$ [10]. This is, again, expected since usually the dominant interaction that distinguishes left-handed from right-handed particles is the weak interaction. Yukawa interactions with the Higgs also distinguish between left- and right-handed quarks. In our scenario, with Yukawa couplings of order one, the Yukawa interaction gives the dominant contribution and lifts this suppression factor too. Thus, in our scenario, there is no parametric suppression of n_B/s, but there are still numerical suppression factors, $\frac{1}{T}\int\frac{d\omega}{2\pi}n_0(\omega)(1-n_0(\omega))f_9(\omega) \sim 10^{-3}$ (where $f_9(\omega)$ is defined in ref. [10]). Combined with the explicit factor of 10^{-3} in eq. (6), related to g_* (the number of relativistic degrees of freedom), it leads to a suppression of n_B/s by $\mathcal{O}(10^{-6})$.

At this stage, we cannot make a more precise statement about the size of n_B/s in our scenario. The reason is not only that the precise values of the (order one) Yukawa couplings before EWPT are not known, but also because the calculation is different from the light quark case in several important ways.

1. In order to calculate eq. (6), a picture of quasiparticles was introduced, where the massless quarks acquire a complex effective mass due to interactions with the hot plasma. In the standard picture, there are several mass scales: the light quark masses (m_d, m_s), the typical momentum difference between left- and right-handed quarks ($\sim$ 6 GeV) and the critical temperature ($\sim$ 100 GeV). The clear hierarchy between these scales in the standard scenario no longer exists, and various approximations based on the hierarchy are not valid.

2. To calculate $\Delta(\omega)$, an effective Dirac equation is employed for the quasiparticles. It takes into account the damping rate for the quasiparticles at zero momentum, $\gamma \simeq 0.15 g_s^2 T \sim 20$ GeV. For particle momenta that are not much smaller than the temperature, there may be large corrections to this result. Furthermore, the effective Dirac equation has been solved by treating the quasiparticle masses as perturbations [10]. The perturbative expansion is valid only for $m_q/6\gamma \ll 1$. Within the standard scenario, this is a good approximation to all but the top quark. In our case, this is a questionable approximation for all quarks.

Therefore, our analysis above should be used only to identify the small parameters which still play a role in suppressing the baryon asymmetry (and those which do not). It should not be taken for a reliable estimate of other, apriori order one, factors.

The Electroweak Phase Transition. In order for EW baryogenesis to successfully produce the baryon asymmetry, it is necessary that the EWPT is first order. The condition of first order phase transition is commonly quantified by demanding that baryon number that was produced during the phase transition will not be diluted by baryon violating interactions inside the bubble. By calculating the rate of interactions, one obtains the sphaleron bound on $\langle\phi\rangle$, the VEV of the SM higgs (for a pedagogical review, see [12]):

$$\langle\phi(T_c)\rangle/T_c \gtrsim 1.3. \tag{7}$$

The VEV is related to the Higgs mass and so the above constraint is translated to a constraint on the mass of Higgs which, at one loop, reads:

$$m_h \lesssim 42 \text{ GeV}. \tag{8}$$

Such a low value (and the somewhat weaker bound when higher loops are taken into account) is experimentally ruled out. Thus, not only CP violation has to have new sources, but also the EWPT has to be different from the SM one, i.e. the scalar sector must be extended.

In our scenario, the Higgs mass is, in general, different from its present value. As can be seen from eq. (5), the corrections are of order $m_W^2\left(\frac{S^\dagger S}{M^2}\right) = \mathcal{O}(m_W^2)$. The change is then significant and could easily take the Higgs mass to be low enough at the time of EWPT to make it first order.

Conclusions. The Standard Model fulfills all three Sakharov's conditions that are necessary for baryogenesis. The failure of the Kobayashi-Maskawa mechanism to account for the observed baryon asymmetry is related to the numerical values of the Standard Model parameters. The smallness of the quark flavor parameters (masses and mixing angles) suppresses CP violation too strongly, while the mass of the Higgs boson is too heavy for a first order electroweak phase transition to occur.

The possibility that there have been time variations in the Yukawa couplings opens up a window for the Kobayashi-Maskawa phase to be the only source of CP violation and to drive baryogenesis. Within the Froggatt-Nielsen framework, where the structure of the flavor parameters is a result of an approximate horizontal symmetry, it is plausible that the time variation has been such that all flavor parameters were order one at early times.

The dynamics of electroweak baryogenesis when none of the quarks is much lighter than the electroweak breaking scale may be quite different from the case of light quarks and needs to be carefully investigated. There are no obvious parametric suppression factors and the produced baryon number may even be as large as $\mathcal{O}(10^{-6})$. We conclude that the observed baryon asymmetry can be explained by the KM mechanism, provided that there are no strong dilution factors coming from the dynamics.

The possibility that there has been time variation in the Higgs potential parameters opens up a window for the EWPT to be first order with only the single Higgs doublet playing a direct role.

It is worth emphasizing that our scenario can also be implemented in the supersymmetric framework. The Froggatt-Nielsen selection rules are somewhat different [13], but the analysis presented here is unchanged. The EWPT could be first order even without time variations in the couplings. While in generic supersymmetric models there are additional sources of CP violation that affect baryogenesis, our mechanism is particularly interesting for models of minimal flavor violation, where the CKM matrix is the only source of flavor and CP violation.

Our scenario introduces a loophole in the commonly held view that the Kobayashi-Maskawa mechanism cannot be the only source of CP violation to play a role in baryogenesis.

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* Incumbent of the Recanati Career Development chair for energy research; Electronic address: micha.berkooz@weizmann.ac.il
† Electronic address: yosef.nir@weizmann.ac.il
‡ Electronic address: tomer.volansky@weizmann.ac.il

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